

# **RUNWAY INCURSION PREVENTION: A TECHNOLOGY SOLUTION**

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## **Abstract**

A runway incursion occurs any time an airplane, vehicle, person or object on the ground creates a collision hazard with an airplane that is taking off or landing at an airport under the supervision of Air Traffic Control (ATC) [1]. Despite the best efforts of the Federal Aviation Administration (FAA), runway incursions continue to occur more frequently. The number of incursions reported in the U. S. rose from 186 in 1993 to 431 in 2000, an increase of 132 percent. Recently, the National Transportation Safety Board (NTSB) has made specific recommendations for reducing runway incursions including a recommendation that the FAA "require, at all airports with scheduled passenger service, a ground movement safety system that will prevent runway incursions; the system should provide a direct warning capability to flight crews" [2]. To this end, NASA and its industry partners have developed an advanced surface movement guidance and control system (A-SMGCS) architecture and operational concept that are designed to prevent runway incursions while also improving operational capability. This operational concept and system design have been tested in both full-mission simulation and operational flight test experiments at major airport facilities. Anecdotal, qualitative, and specific quantitative results will be presented along with an assessment of technology readiness with respect to equipment.

## **1 Introduction**

Traditionally, pilots have relied on visual aids such as airfield markings (e.g., painted centerlines), signs, and lighting, in conjunction with a paper chart of the airport to navigate from point to point on the surface (Figure 1). Pilots use a radio channel to obtain from ATC a route to follow while on the surface. Generally, a "ground" controller will issue this taxi route to pilots using explicit instructions and a strict protocol (i.e., phraseology) so that there is no misunderstanding of voice communications. The pilot must then memorize this route, or write it down, re-state it to the controller for confirmation, and then follow the signs and markings to the destination while avoiding other surface traffic and obstructions. Meanwhile, the ground controller must remember the routes given to all aircraft and monitor aircraft movements so that

no one is directed into a potential conflict. If there is a potential for conflict, hold-in-position instructions can be issued over the radio channel to constrain aircraft movements.



**Figure 1. Pilot Perspective During Surface Operations<sup>1</sup>**

Flight crews perform surveillance on the airport surface using primarily the “see and avoid” principle to maintain safe separation. Similarly, ATC performs the surveillance task based primarily on visual cues. Occasionally, both pilots and controllers will use radio communications to confirm positions of relevant traffic. While the Traffic Alerting and Collision Avoidance System (TCAS) provides traffic advisories to flight crews in flight, it is not intended for use on the airport surface. The Airport Surface Detection Equipment (ASDE-3) radar is used in the U. S. to provide secondary surveillance data to the ATC tower; however, it is currently only scheduled to be deployed at 34 U. S. airports. ASDE-X, a follow-on airport surveillance system, is intended for deployment at an additional 25 towered airports.

The traditional procedures have worked well in the past as airport surfaces have not been congested and visibility is usually good. However, as the traffic volume has increased, the airport surfaces have become more and more congested even in clear weather. This congestion has led to a need to perform more operations in low visibility and at night. Further, the ever-increasing demand has led to increasingly complex airport layouts. The traditional procedures and technologies have not been designed to accommodate these situations. It is believed that the rising trend in runway incursion statistics is an indirect effect of this design limitation.

By definition, a runway incursion occurs any time an airplane, vehicle, person or object on the ground creates a collision hazard with an airplane that is taking off or landing at an airport under the supervision of ATC [1]. To improve safety with respect to runway incursions, two capabilities are required of a surface movement guidance and control system. The first focuses on avoidance, while the second focuses on detection. Each will be described separately.

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<sup>1</sup> Airport chart courtesy Jeppesen

## **1.1 Runway Incursion Avoidance**

Avoidance describes the ability of a flight crew to reduce the likelihood of inadvertently entering an active runway. Unfortunately, this likelihood can never reach zero due to human nature, hence the need for a detection function as well. In today's environment, the avoidance function is implemented prior to a particular operation through training, planning, and experience; and during the operation by the procedures describe above: movements controlled and monitored by ATC and pilots performing "see-and-avoid". Note, there are no technologies or systems on-board today's aircraft to help pilots avoid incursions.

In the operational environment, the key information pilots need to avoid runway incursions is (1) own-ship location, (2) traffic locations, and (3) route and routing constraints as issued by ATC [3]. Maintaining adequate levels of these elements of situational awareness (SA) also requires knowledge of the airport layout. For example, knowing that an aircraft is at a particular latitude/longitude provides no useful information with respect to avoiding runway incursions. Therefore, the three elements listed above must be known relative to the particular airport layout.

With respect to route and routing constraints on the airport surface, pilots must have confidence that this information, as provided by ATC, is correct. This implies that runway incursion avoidance also describes the ability of ATC to reduce the likelihood of inadvertently issuing an incorrect instruction or clearance. Again, due to human nature, this likelihood can never be zero, hence the need for a detection function. However, this likelihood can be reduced if ATC has good SA with respect to the location and identity of traffic relative to the airport layout.

## **1.2 Runway Incursion Detection**

Detection describes the ability to become aware that an incursion has occurred so that evasive action can be taken, if necessary, to avoid a conflict. As described above, due to human nature, we can never reduce the probability of runway incursion to zero. Additionally, at least in the near-term, it is unlikely that all aircraft and airport facilities will be equipped with avoidance technologies like the ones described later in this report. Based on these two facts, a means of timely detection is required.

There are several ways to detect incursions in the current operational environment. In good visibility, diligent visual scans by pilots and controllers are the best detectors. Occasionally, incursions can also be detected by listening to the communication channels. There are two fundamental problems with using only these detection mechanisms. First, since runway incursions are rare events (five runway incursions every million operations [1]), maintaining diligent visual scanning and monitoring of route conformance naturally lends itself to complacency, or at best, a low priority task, especially in the presence of high workload. Second, even when an incursion is detected visually either by a pilot or by a controller, there is often insufficient time to take action to avoid conflict.

Three other issues directly affect timely detection of incursions: (1) limited visibility due to fog or darkness, (2) radio congestion, and (3) airport layout complexity. The combination of these three issues can make timely detection of runway incursions nearly impossible in some cases.

### **1.3 Section Synopsis**

The remainder of this paper has been partitioned into sections that focus on how technology might be used to improve safety with respect to airport surface movements. Specifically, Section 2 reviews runway incursion causal factors and presents a summary of past work. Section 3 describes the system approach that is the result of joint NASA/FAA/industry research and development. Sections 4 and 5 provide results of a recent flight simulation study and subsequent flight test experiment. Section 6 discusses some of the implementation issues, constraints, and challenges. Section 7 summarizes the report. Attached at the end of the document are brief author biographies, a list of acronyms, and a list of references.

## **2 Background**

A recent publication by the FAA [1] assessed the relative severity of runway incursions. In the period 1997 to 2000, 1369 incursions were reported at the more than 450 towered airports in the U. S.; three of these resulted in accidents. Most of these incursions were found to be minor, in that the risk of collision was very low. However, at the busiest airports, it was found that the rate of incursions, where there was a high risk of collision, was twice as great as for the remaining airports. When incursions are investigated, the FAA attributes the cause to (1) an operational error (an error by ATC), (2) a pilot deviation (an error by a pilot), or (3) a vehicle/pedestrian deviation (unauthorized movement by a vehicle or pedestrian). Pilot deviations were found to be the leading cause (60%) of the incursions that were reported between 1997 and 2000. Operational errors accounted for 20% during this same period.

If we assume that errors by ATC and pilots are inadvertent, then 80% of the reported runway incursions could have been avoided had these individuals had sufficient situational awareness during the operation with respect to the information elements described in Section 1; namely own-ship position, traffic positions, and route, all relative to the airport layout.

### **2.1 FAA Investments**

Runway incursion mitigation strategies implemented to date by the FAA include: (1) the publication of guidance material for pilots and controllers to heighten awareness of the hazard potential, (2) the installation of improved signage and markings at airports that are easier to follow, and (3) installation of improved lighting systems to support surface movement guidance [4]. Each of these has helped to reduce the likelihood of incursions; however, the latter two are only of benefit at those airports where the improvements have been made.

Other technologies pursued by the FAA offer a great deal of potential, but have yet to be installed and used extensively in the operational environment. For example, the FAA continues to investigate upgrades to surface surveillance technology to support ATC responsibilities. Technologies such as ASDE-3/ASDE-X radars, multi-lateration systems, and in-pavement loops have been tested; and development continues toward possible wide-spread installation. Also, the Airport Movement Area Safety System (AMASS) has been developed with the hope of detecting hazardous situations on the surface and alerting ATC using data derived from an airport surveillance system.

The Runway Status Light System (RWSL), prototyped in the mid 1990's, consists primarily of red lights installed at runway/taxiway intersections. These lights illuminate when a runway is deemed unsafe to enter. Similar lights are located at take-off positions to warn of traffic crossing down the runway. The light state is driven by real-time surveillance information and as such the lights function independently of ATC. Pilots approaching an active runway monitor the lights while also performing a visual scan thus reducing risk while crossing the runway. Until recently, RWSL has been the only technology investigated by the FAA that is aimed at directly informing pilots, during the operation, of unsafe situations on the airport surface. Simulation studies and proof-of-concept operational tests have demonstrated the RWSL potential; unfortunately, it has yet to be implemented.

Finally, the FAA has recently sponsored an effort called "Safe Flight 21". One of the operational enhancements envisioned by this project is to provide a cockpit display of traffic information during final approach and on the airport surface [5]. This would enable improved detection of runway incursions.

## **2.2 NASA Investments**

While the FAA has focused its efforts primarily on airport infrastructure and training, NASA has sponsored research aimed primarily at improving situational awareness in the flight deck to help prevent runway incursions. For the most part, NASA and FAA investments in runway incursion prevention have been complementary and synergistic.

Specifically, NASA developed two display concepts that were assessed extensively in full-mission simulation and in flight. The first provided flight crews with a real-time graphical display indicating own-ship position relative to airport features (such as taxiway edges), traffic locations, and taxi route [6][7]. The second provided guidance to flight crews between touchdown and runway exit on a Head-up Display (HUD). This enabled safe and efficient landing roll-out and turn-off regardless of visibility conditions [8]. These concepts were integrated and flown on NASA's B-757 test aircraft at the Atlanta airport in 1997 [3]. This testing represented the first implementation of an aircraft-based A-SMGCS. The portion of this system that provided HUD guidance has since been migrated to industry and is being certified by Rockwell Collins Avionics Flight Dynamics [9].

Based on the previous work described above and a close working relationship with the FAA and industry, a system design has evolved that has the potential to significantly reduce the likelihood of runway incursions in the future. This system design is described in the following section.

## **3 System Architecture**

To improve runway incursion avoidance and detection capabilities, a system architecture can be implemented using a functional building-block approach based on the operational requirements of a particular airport and/or the investment strategy taken by the operators and the airport. Each of these functions can be supported by technology. Table 1 lists five functional elements of the system. Table 1 also lists the recommended component technologies that can be used to improve avoidance and detection capabilities during operations. These specific technologies have been chosen based on operational readiness and performance observed during flight test experiments.

**Table 1. System Functions and Component Technologies**

| <b>Function</b>                | <b>Aircraft Technologies</b>        | <b>Airport Technologies</b>           |
|--------------------------------|-------------------------------------|---------------------------------------|
| 1. Own-ship Position Awareness | GPS, AMDB, Display                  | ---                                   |
| 2. Traffic Position Awareness  | GPS, AMDB, Display<br>ADS-B, STIS-B | AMDB, Display<br>ADS-B, STIS-B, Radar |
| 3. Route Awareness             | AMDB, Display<br>CPDLC              | AMDB, Display<br>CPDLC                |
| 4. Route Deviation Detection   | GPS, AMDB, Display<br>CPDLC         | Display<br>CPDLC                      |
| 5. Runway Incursion Detection  | (Same as 2)                         | (Same as 2)                           |

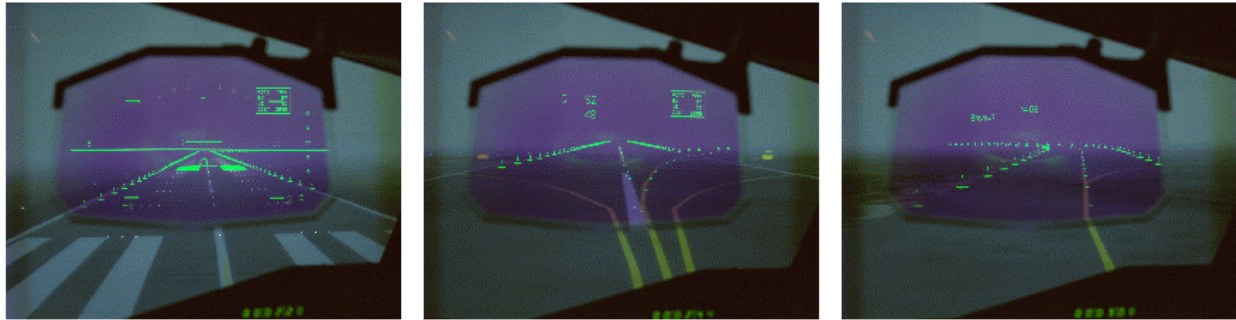
### **3.1 Own-ship Position Awareness**

Position awareness can be improved in flight decks using the Global Position System (GPS), an Airport Mapping Database (AMDB), and a display. Several existing displays can support this function including HUD and Navigation Displays (NDs). Using these technologies, pilots can determine (1) their position relative to runway/taxiway edges, (2) which runway or taxiway they are currently on, and (3) the names and locations of intersecting runways or taxiways. In ramp areas, gate locations can be shown. When accurate centerline data is included in the AMDB, tactical guidance similar to a flight director can be provided. If available, inertial data can be integrated with GPS to improve performance. Examples of this display concept are shown in Figures 2 and 3, and again in Section 4. Even if the other functional elements listed in Table 1 are not implemented, this functional element would be a significant aid in avoiding inadvertent runway incursion by reducing the likelihood of pilot deviation. Some operational errors may also be detectable by pilots using only this function.

### **3.2 Traffic Position Awareness**

Both pilots and controllers can improve SA with respect to traffic by having access to a graphical display of the airport layout overlaid with current accurate traffic symbols. Examples of a track-up flight deck display are shown in Figure 3 and in Section 4. An AMDB is essential to implement this function. Both pilot and controller displays of traffic should use the same AMDB. In addition to the AMDB, a surveillance capability is required. Ranging sensors on-board aircraft (e.g. radar) can be used; however, the development of Automatic Dependent

Surveillance – Broadcast (ADS-B) transponders seems to provide a more cost-effective solution at this time. In addition, to cover traffic that is (1) not equipped with an ADS-B transponder, or (2) operating with a failed transponder, a surface radar capability is also recommended. The airport radar data can then be broadcast to aircraft to ensure that all traffic data is available. This data link application is called Surface Traffic Information Service – Broadcast (STIS-B).



**Figure 2. Improved Own-ship Position Awareness using HUD**

### 3.3 Route Awareness

To help avoid runway incursions caused by pilot deviations, taxi route and routing constraints can be displayed in the flight deck. Examples of this display concept are shown in Figure 3. Again, an AMDB is essential to implement this functional element. Pilots can refer to a graphical depiction of the approved route (and any hold-short points) as needed during the operation to reinforce the clearance they obtained over the radio. To enable display of route, pilots could manually enter it into the on-board system or select it from a menu of standard routes; however, Controller-Pilot Data Link Communications (CPDLC) is recommended. CPDLC can capture ATC instructions verbatim and transmit them to aircraft for display. This function can all but eliminate pilot deviations. Operational errors can still happen, but a graphical display of an inappropriate route or clearance may allow for detection by pilots.



**Figure 3. Improved Position, Route, and Traffic Awareness using ND**



### 3.4 Route Deviation Detection

Using GPS, an AMDB, and CPDLC, pilot deviations from route, or from hold-short locations, can be detected on-board the aircraft. After detection, the system can inform both the pilot via his display and the controller via CPDLC. Early detection of pilot deviations in this manner should greatly reduce the number of incursions that occur, as it will provide additional time to recover before maneuvering into a hazardous situation.

### 3.5 Runway Incursion Detection

If current accurate traffic information is available, runway incursions can be detected automatically by this function. As mentioned previously, traffic positions can be sensed by aircraft (via radar), or received via data link from transponders (ADS-B) or from the airport facility (STIS-B). The detection function also requires GPS and an AMDB so that hazard potential can be assessed. Once detected, alerts can be generated; analogous to TCAS operation in-flight. Examples of this display concept are shown in Section 4. This function can provide the most important element to avoiding conflict in the presence of runway incursion – time.

## 4 Flight Simulation

Four of the five system functions described in Section 3 have been verified to a degree by previous flight simulations and two flight tests [3][10]. However, these tests have not included an incursion detection function. A simulation study using airline pilots has been conducted to evaluate the addition of this function. This section provides an overview of this study [11].



**Figure 4. Simulation Display Configuration**



The system was implemented using a fixed-based simulator cab and a remote ATC position. The simulator consisted of an all-glass flight deck that implemented the standard displays as well as a HUD (Figure 4). B-757 vehicle dynamics were used for all simulations. The airport environment that was modeled was the north side of ATL operating at near-peak capacity. In this case, near-peak capacity consisted of an inter-arrival spacing of three nautical miles between touchdowns and an inter-departure rate of 90 seconds between take-offs.

To implement the display component of the architecture in the simulator, the HUD and ND capabilities were extended to include not only their standard capabilities, but also those functions proposed by this paper. Figure 4 depicts the simulator configuration for the experiment. The HUD was used for tactical guidance during final approach, landing, roll-out, turn-off, and taxi. During landing roll-out, deceleration guidance to a pilot-chosen exit was provided along with centerline and runway edge symbology. During taxi, centerline and taxiway edge symbols were provided on the HUD only along the ATC-approved route. These features were provided to improve own-ship position awareness as was previously done in [3].

An Electronic Moving Map (EMM) mode was added to the standard suite of ND modes. If the pilot, or co-pilot, selected EMM mode, the ND would show the airport layout along with the current position of the own-ship, current positions of other traffic, and ATC instructions. ATC instructions were depicted both graphically and textually. Graphic depictions of ATC instructions included the approved route and any hold-short locations. Several zoom/scale levels were available to pilots when using this ND mode. This ND mode was provided to supplement awareness of position, traffic, and route as was previously done in [3].

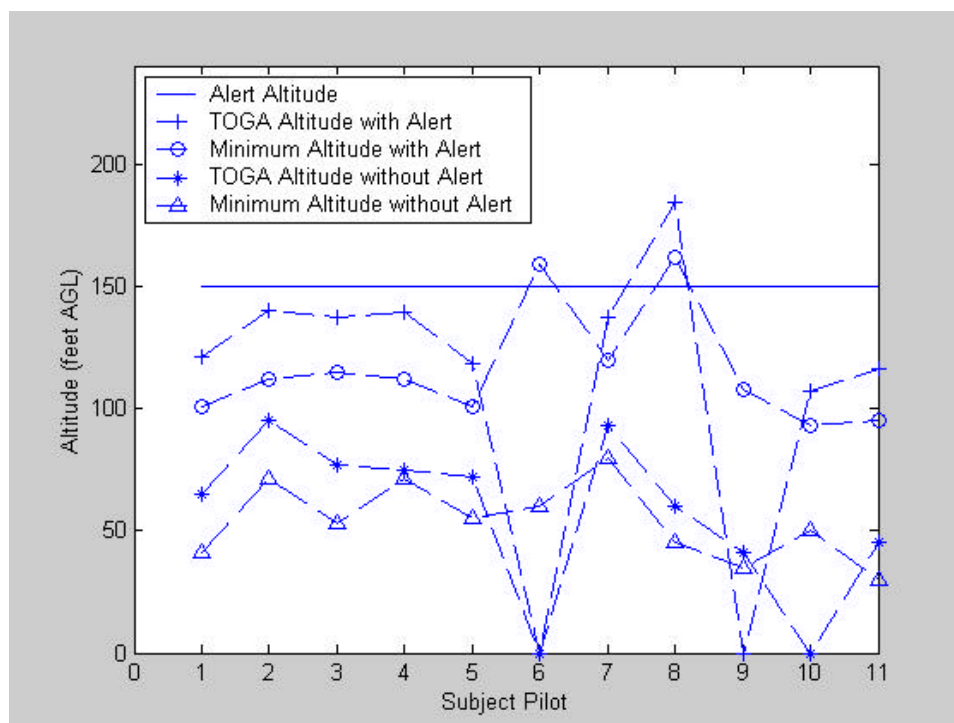
Runway incursions and route deviations were also detected. Once detected, incursion alerts were generated and consisted of an audible enunciation of the phrase “Runway Traffic, Runway Traffic” in the flight deck. These alerts were also presented textually on both the HUD and the EMM. On the EMM, the traffic symbol representing the incurring aircraft/vehicle changed color and flashed (Figure 5). The system monitored the runway for incursions by other aircraft during own-ship takeoff roll and during final approach. The system also detected deviations from the assigned taxi route and sent them to the test controller position.



**Figure 5.** EMM during Departure (left) and Arrival (right) Runway Incursions

The test matrix consisted of four control variables: the crew, the display configuration, the airport configuration, and the visibility conditions. As these variables changed from run to run, the operational task remained the same for either an arrival or departure scenario. For arrival scenarios, the simulator was initialized five nautical miles out, on the glide-slope and localizer for the outer runway. For departure scenarios, the simulator was initialized at ramp locations (after pushback). Two specific runway incursion scenarios were implemented. Infrequently, during final approach, an aircraft would taxi onto the active runway in front of the own-ship (Figure 5). If the crew detected the incursion, either visually or based on an alert, they were instructed to perform an immediate go-around. The second incursion scenario occurred during a departure. On take-off roll, an aircraft would taxi onto the runway in front of the own-ship near mid-field (Figure 5). If the incursion was detected, the crew was instructed to abort the take-off.

Three-person teams (captain, first-officer, and controller) performed 24 scenarios using a particular airport configuration. After switching the airport configuration and the captain/first-officer positions, 24 additional scenarios were completed by each team. In total, 432 scenarios were completed, 54 of which included runway incursions. 18 active airline pilots and six active air traffic controllers participated. Average flight experience for the pilots was 10,600 hours.



**Figure 6. Incursion Detection on Final Approach During Simulation**

Several valuable insights were obtained while conducting this experiment. For example, Figure 6 compares the minimum altitudes prior to go-around for the arrival incursion scenarios. The incursions, and the ensuing alerts, for all of the data shown occurred in 1200 feet visibility (Category II minima) with own-ship only 150 feet Above Ground Level (AGL). Descent rate was about 10 feet per second. Notice that the automatic detection and alerting system resulted in approximately six additional seconds (60 feet of altitude) for the pilot to avoid the conflict.

Average reaction time to the alert was about two seconds. This can be determined by observing the delay in engaging the Take-off Go-around (TOGA) mode of the autopilot. Note in Figure 6 that pilots 6, 9, and 10 did not engage TOGA but chose to perform the go-around manually.

Figure 6 also shows that without the automatic detection, a collision probably would have resulted in some cases. Pilots 1, 8, 9, and 11 were below 45 feet AGL when they started climbing. This is less than the height of some aircraft tail sections. Finally, Figure 6 shows that detection can also be accomplished by strict monitoring of the cockpit traffic display. In this manner, pilots 6 and 8 detected the incursion and performed the go-around before the automatic alert was triggered.

Questionnaire data was also solicited from the subjects and can be summarized as follows. Both pilots and controllers were unanimous in supporting the operational concept in general. To maintain safety and efficiency, pilots felt the EMM would be sufficient to Category II minima (1200 feet), but head-up guidance may be needed for Category III-A and III-B minima (700 and 150 feet). Pilots suggested that maneuver guidance following incursion detection was desirable. The audible incursion alerts were noted as an appropriate means of informing the crew. All pilots said they felt “safer” having this technology onboard. ATC test subjects also supported the concept viewing CPDLC as an important tool assuming adequate performance.

Finally, the data suggests that further investigation into the automatic onboard detection of runway incursions is justified. While pilot detection of runway incursions based solely on strict use of a traffic display may be sufficient to catch the majority of incursion situations, this requires close monitoring of the displayed runway on short final approach or departure roll. This additional workload and the probability of human error must be traded against a non-zero probability of missed detection and false alarm associated with automatic detection schemes. To gain more insight into this issue as well as technology readiness, a flight test of the system concept was conducted.

## **5 Flight Testing**

All five functions listed in Section 3 were tested at DFW [10]. The objectives of the testing were to demonstrate one particular implementation of these functions and to evaluate the performance of the technologies used in this implementation. Components of the system were installed on NASA’s B-757 research aircraft, a test van that emulated an aircraft on the surface, and an experiment-specific airport facility. The experimental flight deck displays described in Section 4 were implemented on the test aircraft. To enable the display functions, an AMDB for the DFW airport was developed based on the requirements specified in [12]. The specified accuracy for all elements of this AMDB was 0.3 meters. To meet NASA flight test policy, no experimental displays were installed for the right-seat pilot. As such, the HUD and the EMM mode of the ND were only available to the left-seat pilot.

### **5.1 Runway Incursion Detection Methods**

At DFW, three methods of automatic runway incursion detection were tested and will be denoted in this paper as the Runway Safety Monitor (RSM), the Runway Incursion Advisory and Alerting System (RIAAS), and the Ground-Based Alerting (GBA) system.

The RSM executed autonomously on the test aircraft and monitored traffic position reports received via data link. Potential for incursion was identified by RSM any time individual traffic position reports entered a three-dimensional virtual protection zone around a runway being used by the test aircraft. This protection zone extended 1.1 nautical miles from the runway threshold, 220 feet from the edges of the runway, and 400 feet vertically. Detection of incursions was based on the operational state of the own-ship, traffic, and other criteria such as separation and closure rate, to help reduce the likelihood of false alerts.

RIAAS [13] operated on the same general premise as RSM, utilizing runway zones and tracking of traffic within that zone. However, RIAAS detected incursions based not only on the states of own-ship and traffic, but also on unique criteria associated with specific scenarios. State was determined by the location relative to the runway, speed, track angle, and acceleration. RIAAS was designed to handle over forty specific runway incursion scenarios. RIAAS generated two types of alerts that are analogous to the TCAS approach. A Runway Traffic Alert (RTA) cautioned the flight crew of a potential incursion or an incursion where the conflict did not yet require evasive action. A Runway Conflict Alert (RCA) occurred when an actual runway incursion was detected and an evasive action was required to avoid a potential collision.

The GBA approach was to transmit to the test aircraft, via data link, incursion alerts that were generated by the FAA's ground-based surveillance system. These were generated using a subset of scenarios used by the AMASS. The AMASS safety logic was only applied to traffic that was on the runway or in its approach corridor. Alerts were generated when two targets fell within a separation distance threshold and transmitted via STIS-B along with the traffic location data.

Following incursion detection, alerts were presented to the flight crew both audibly and visually as described in Section 4 with the following exceptions: (1) in some cases, the phrase "Runway Conflict, Runway Conflict" was used for the audible and textual alerts; and (2) information was added beneath the own-ship symbol on the HUD and EMM indicating the distance to the incurring traffic and time until potential collision at present conditions.

## **5.2 ATC Display and CPDLC**

By interfacing to the surveillance system described below, an experimental display and data link capability enabled all of the ATC functions described in Section 3. A test controller had access to a graphic display of DFW overlaid with real-time airport traffic. Instructions for the test aircraft were captured via voice recognition and transmitted via CPDLC for display in the flight deck. Runway incursions detected on-board the B-757 were sent to the ATC system via the same two-way data link for display to the controller. Incursions detected by the GBA method were also displayed. Finally, route deviations detected by the aircraft system were data linked to this ATC system. This technology is described in more detail in [14].

## **5.3 Own-ship Position Determination**

A prototype Local Area Augmentation System (LAAS) ground reference station was installed at DFW to support both surveillance and guidance functions [15]. Throughout most of the testing, the real-time display of position was determined by blending LAAS position solutions with position solutions from the on-board inertial system. A Wide Area Augmentation System

(WAAS) receiver was also installed on the test aircraft [16]. The WAAS data was recorded and was not used for real-time positioning during the testing.

#### **5.4 Traffic Position Determination**

Two methods of acquiring traffic position data onboard the research aircraft were tested: ADS-B and STIS-B. The STIS-B data was sent from the airport facility and is described in the surveillance system section below. At DFW, ADS-B messages were broadcast from the research aircraft and test van as specified by [17]. The messages contained information such as position, altitude, speed, and heading. The position information was obtained from a GPS receiver using differential corrections provided by LAAS. ADS-B messages were transmitted at a nominal rate of twice per second.

#### **5.5 Surveillance System**

The FAA installed an experimental surveillance system at DFW to support the testing. This system acquired information on traffic in the airport terminal area from several sources, fused this information, and then transmitted this traffic data to the test aircraft. One source was the ASDE-3 radar. ASDE-3 is designed to provide position data (range and azimuth) to ATC at a rate of once per second and does not require any equipage on aircraft or vehicles. Although the ASDE-3 is a high performance radar system, it still has certain limitations. Complete airport surface coverage is not always achievable with a single ASDE-3 since it is a line-of-sight radar. Also, false targets can be reported from multi-path reflections. Finally, the ASDE-3 does not report target identification. To augment these limitations, an Airport Target Identification System (ATIDS) was installed on the east side of the DFW airport. ATIDS is a multi-lateration system designed to track and provide identification information for aircraft and ground vehicles that have operating transponders. Fused reports from these sensors were transmitted via data link to the test aircraft using a Universal Access Transceiver (UAT) operating at 966 MHz. This application of data link technology is referred to as STIS-B. The same traffic data was also provided to the test controller via a local area network for display.

#### **5.6 Flight Test Operations**

There were four types of scenarios tested at DFW. These scenarios were designed to emulate the most common runway incursion incidents. For the first scenario, the test aircraft was landing with auto-land engaged while the test van was located behind the hold line at a taxiway near the runway threshold. When the aircraft was approximately 1.25 nautical miles from the threshold, the test van began crossing the runway. This scenario most closely matched the scenario tested during the simulation study previously described in Section 3. For the second scenario, the test van was located behind the hold line at a taxiway at the far end of the departure runway. The test aircraft began take-off roll and then the test van began crossing the runway. For the third scenario, the test aircraft was the incurring vehicle and the test van was emulating an aircraft on departure. The test aircraft was holding at a taxiway at one end of the runway. The test van began its accelerating from the opposite end of the runway. Once the van reached 70 miles per hour, the test aircraft began crossing the runway. Finally, for the fourth scenario, the test aircraft was landing with auto-land engaged. When the aircraft was approximately 1.25 nautical miles from the threshold, the test van entered the runway mid-field and began traveling down the

runway, accelerating to 70 miles per hour, away from the test aircraft as if it was a departing aircraft. In total, 47 runs were completed using four commercial B-757 captains as test subjects.

## 5.7 Results

The three incursion detection methods were executing concurrently during the testing, however, only one method was chosen for each run to drive the flight deck displays. Table 2 shows the overall performance of each of the detection methods. All of the missed detections for RSM and RIAAS were a direct result of erroneous or missing traffic data from the STIS-B and/or ADS-B sources. For GBA, the missed detections were the result of the GBA detection criteria and scenario timing.

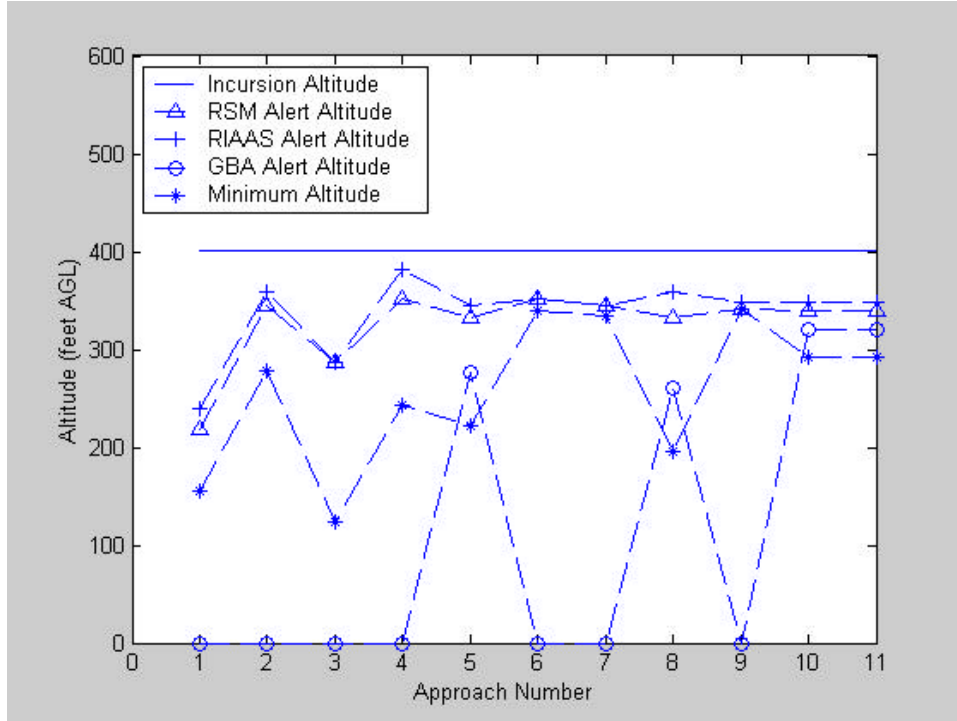
**Table 2. Detection Method Performance**

| Scenario          | Runs | Incursion Detections |       |     |
|-------------------|------|----------------------|-------|-----|
|                   |      | RSM                  | RIAAS | GBA |
| 1                 | 12   | 11                   | 11    | 8   |
| 2                 | 11   | 10                   | 11    | 9   |
| 3                 | 12   | 11                   | 10    | 6   |
| 4                 | 12   | 11                   | 12    | 11  |
| Total             | 47   | 43                   | 44    | 34  |
| Missed Detections |      | 4                    | 3     | 13  |
| False Alerts      |      | 4                    | 2     | 9   |

For the approach scenarios, generally the RIAAS RTA occurred a few seconds before the RSM alert. Usually 5 to 10 seconds later, the GBA alert was generated. The RIAAS RCA would then occur 5 (Scenario 1) to 15 (Scenario 4) seconds after that. For the departure scenarios, the RIAAS RTA was generated first, followed usually one to five seconds later by a RIAAS RCA. The RSM alert was generated approximately the same time as the RIAAS RCA. Finally, the GBA would alert 10 to 20 seconds later.

It is interesting to compare the performance of the incursion detection function as implemented in flight (Figure 7) with the function as implemented in the simulation study (Figure 6). The approaches shown in Figure 7 represent Scenario 1 flights. The test aircraft is on short final as the test van moves onto the runway at the approach end. This emulates the simulation scenario previously described. One difference is that the van enters the runway when the test aircraft is nominally 1.25 nautical miles from the threshold; this corresponds to about 400 feet AGL on a three-degree glide-slope. In the simulation, 150 feet AGL was used to trigger movement of the incurring vehicle. As can be seen the minimum altitude for all of the approaches is 124 feet with most above 200 feet. In both the simulation and in flight, about 50 feet of altitude (five seconds) is lost after the alert has been generated. This delay includes pilot reaction time and the time required to level-off the aircraft (reduce sink rate to zero). Finally, note that for most of the approaches shown in Figure 7, the GBA alert altitude is indicated by zero. For these cases, either the GBA did not detect an incursion by 150 feet AGL, or the pilot was alerted by one of the other detection methods and initiated go-around before the GBA incursion criteria was met.





**Figure 7. Incursion Detection on Final Approach During Flight Test**

Next, consider navigation system performance. As described in [18], at large airports, the navigation system accuracy should be no worse than 2.2m (95% horizontal circular error probability (CEP)) for safe operations on the surface movement area in low visibility conditions. Using the concept described in this paper, this budget must account for not only the positioning system accuracy, but also the AMDB centerline accuracy and flight technical error (FTE). For DFW, the airport database accuracy for centerline data is specified to be 0.3 meters. FTE has not been assessed.

For positioning system performance analysis, truth data was obtained by post-processing GPS data using a well established carrier-phase interferometry technique that is often used in the surveying practice. Using this data as a reference, a preliminary assessment of the accuracy achieved at DFW suggested a 95% horizontal CEP of 4.48 and 2.61 meters for WAAS and LAAS, respectively. The LAAS performance was nearly equivalent to performance of a Special Category I differential GPS system used during trials at ATL in 1997 [3]. Availability was found to be 92.08% and 95.05% for WAAS and LAAS, respectively. The integration of LAAS solutions with inertial solutions improved availability to 98.32%, reduced the variance, and provided the high update rate needed for display.

Two key metrics were assessed with respect to the surveillance system performance during the flight tests. The performance shown in Table 3 is a representative subset of all data and was taken by the ground-based surveillance system while the test aircraft was stationary. Not shown in Table 3 is the ADS-B accuracy. This was equivalent to the LAAS accuracy listed above.

As can be seen, the multi-lateration (ATIDS) outperformed the radar (ASDE-3) with respect to accuracy and update rate. However, neither provided complete coverage on its own. Fusion

enabled full coverage and consistent updating, while sacrificing some of the ATIDS accuracy. Requirements of 12 meters and once per second have been suggested in [19] for accuracy and update rate, respectively, for airport surface surveillance.

**Table 3. Ground-Based Surveillance System Performance**

|                  | ASDE-3 |          | ATIDS |          | Fused |          |
|------------------|--------|----------|-------|----------|-------|----------|
|                  | $\mu$  | $\sigma$ | $\mu$ | $\sigma$ | $\mu$ | $\sigma$ |
| Accuracy (m)     | 11.09  | 0.07     | 3.00  | 0.22     | 10.75 | 0.21     |
| Update rate (Hz) | 1.08   | 0.15     | 2.01  | 4.61     | 3.01  | 0.2      |

The other component of the traffic reporting subsystem tested at DFW was the data exchange between aircraft, or the test van, via ADS-B and between the airport facility and the aircraft via STIS-B. The average update rate during the testing was found to be 0.8 Hz and 1.1 Hz for the ADS-B and STIS-B links, respectively. The average latency, or delay, associated with STIS-B data received on the test aircraft was 2.8 seconds. Although not analyzed, ADS-B latency was observed to be very small (<1 second). This was to be expected as ADS-B delay consisted of only encoding/decoding the message and propagating it over the communication channel. In general, the ADS-B link reliability was very good when the research aircraft was airborne. However, when both test vehicles were on the surface, performance was degraded to about an 80% transmission success rate. This was primarily due to line of sight and multi-path effects. This can be avoided or reduced by a more careful selection of antennas and antenna locations.

The measured performance of the traffic reporting technologies tested at DFW does meet many of the requirements that have been suggested for surveillance on the airport surface [19] and for the traffic awareness function described in this report. However, the performance does not seem sufficient for a robust runway incursion detection function such as the one proposed. This assessment is based on the observed rates of false alerts and missed detections. All false alerts and missed detections at DFW were traced to traffic data that was inaccurate, inconsistent, and/or not received in a timely manner. Further work will seek to establish the requirements for traffic reporting that are needed to support the incursion detection function of the proposed system.

In addition to the observed performance described above, the feasibility of the system concept was also supported by qualitative questionnaire data and comments received from the subject pilots during the testing at DFW. All pilots stated that the system has the potential to reduce or eliminate runway incursions, although human factors issues must still be resolved. Several suggestions were made regarding the presentation of incursion alerts. These will be considered in future simulation studies. The pilots stated that unlike T-CAS, two-stage alerting was not necessary in the case of runway incursions. However, this may be due to the fact that this testing was a single pilot operation and the subject pilot did not have the benefit of co-pilot support.

Lessons-learned with respect to the incursion detection functions tested at DFW can be summarized by the following points: (1) it is essential that reliable, timely, and accurate traffic

data be available, (2) the uplink of incursion alerts generated by a ground-based system is not recommended due to the latencies involved and potential for loss of integrity, and (3) further work is needed to define the requirements for traffic reporting to support the detection function.

Finally, it is important to note that much of the equipment used during the DFW testing was prototype in nature. It is likely that production units would perform significantly better.

## 6 Remaining Challenges and Technology Readiness

When considering implementation of the proposed system, an evolutionary building-block approach is recommended. This is primarily due to the fact that the required component technologies are at various stages of development. Table 4 lists these technologies along with their maturity with respect to operational implementation. Note that only RTCA standards are listed in this table. In many cases, there are also existing EUROCAE and ICAO standards as well as guidance material written by the Society of Automotive Engineers (SAE).

**Table 4. Technology Readiness**

| <b>Technology</b>     | <b>Operational Status</b> | <b>Relevant RTCA Standards</b>   | <b>Functions Supported</b> |
|-----------------------|---------------------------|--|----------------------------|
| Display media         | Certified                 | DO-257   | (1), (2), (3), (4), (5)    |
| GPS                   | Certified                 | DO-202, DO-208, DO-217, DO-228, DO-229B, DO-245, DO-246A, DO-247, DO-253, DO-261 | (1), (2), ---, (4), (5)    |
| AMDB                  | Flight Test               | DO-200A, DO-201A, DO-272   | (1), (2), (3), (4), (5)    |
| ADS-B                 | Flight Test               | DO-242, DO-249, DO-260   | ---, (2), ---, ---, (5)    |
| STIS-B                | Flight Test               | DO-224A, DO-239, DO-243, DO-259  | ---, (2), ---, ---, (5)    |
| CPDLC                 | Flight Test               | DO-224A, DO-250, DO-256  | ---, ---, (3), (4), ---    |
| Airport Surface Radar | Commissioned              | Not applicable   | ---, (2), ---, ---, (5)    |

It is clear from Table 4 that Function 1 (Own-ship Position Awareness) can be implemented almost immediately. Flight-qualified displays and GPS receivers are already installed on many

aircraft. It has also been shown that GPS can be integrated with inertial systems to improve positioning performance. Requirements for AMDBs have recently been written by RTCA and EUROCAE [12]. The most significant challenge will be acquiring the required data to populate AMDBs on a world-wide scale. Developing the prototype AMDBs for ATL and DFW testing revealed that high quality data can be obtained at a relatively low cost (<\$100k) by using proven aerial photogrammetric and/or GPS survey techniques. Cost-sharing between operators and airport facilities may be practical as both can benefit from having this information made available. Once the data is captured, validation, distribution, and maintenance processes must be established; however, as described in [12], this process can follow the one already established for navigation data [20]. Another challenge is to establish an appropriate exchange format for these AMDBs. Finally, if Function 1 is to provide for navigation on the surface in low visibility (e.g. Category III), an augmentation system may be required to provide integrity, availability, and continuity-of-service for GPS. In the U. S., it is believed that WAAS and/or LAAS can be used; however, the existing specifications should be reviewed with respect to surface operations.

Function 2 (Traffic Position Awareness) and Function 5 (Incursion Detection) require additional standards/requirements development to help enable product certification. Although standards exist for ADS-B, these standards do not address surface operations, therefore, revisions are likely required. In addition, there is no standard to support the STIS-B concept specifically. However, other data link requirements documents can provide valuable references when developing a standard for STIS-B, or perhaps this traffic information can be provided as part of the Flight Information Service – Broadcast (FIS-B). Multiple data link technologies have been shown capable of supporting both ADS-B and STIS-B, but due to the incomplete standards mentioned above and interoperability issues, none have been certified on a wide-spread basis. Because ADS-B is more mature, an incremental solution using only this source of traffic data can enable detection of many runway incursions, particularly at large airports where aircraft operating without this type of transponder would be rare.

Function 3 (Route Awareness) and Function 4 (Route Deviation Detection) require CPDLC for optimal efficiency. Although a version of CPDLC is currently undergoing operational testing in Miami, Florida, this version does not include the types of instructions issued during surface operations (e.g. taxi route). These instruction types could be added to subsequent versions based on the implementations used at ATL and DFW. In the interim, standard taxi routes can be established at airports and implemented in Flight Management Systems (FMS). Once received via the radio, pilots could select the appropriate route for display.

For each function, a processing capability is assumed. For retro-fit implementations, it seems appropriate to implement Functions 1, 3, and 4 on the FMS, and Functions 2 and 5 as extensions to TCAS. For forward-fit, application-specific processing capabilities may be more practical.

Finally, two fundamental issues with respect to Function 5 (Runway Incursion Detection) need to be addressed based on evidence taken during the flight tests. The first involves a performance trade-off between strict monitoring of a traffic display by pilots, versus automatic detection of incursions by a system. Essentially, this compares the integrity of human observations with the non-zero probabilities of missed detections and false alarms associated with automated schemes. The second issue to address relates to the operational safety implications of detecting incursions

using a ground-based system that primarily serves ATC versus using an airborne system that primarily serves pilots.

## **7 Summary**

This paper has presented an approach to runway incursion prevention that is based on the assumption that incursions occur primarily due to inadvertent mistakes made by pilots and controllers. The research hypothesis is that if we can improve pilot and controller SA during operations, then the likelihood of these mistakes occurring will reduce. A system architecture has been suggested that makes use of technology to improve SA with minimal impact on current procedures and infrastructure. The system has been functionally decomposed to allow incremental implementation with each function providing an increased level of safety with respect to runway incursion hazards. The operational readiness of specific technologies has also been assessed. Finally, remaining issues that need to be addressed have been identified.

In conclusion, government regulators as well as airport and aircraft operators are encouraged to consider the technology solution that has been suggested in this paper. Although investment is required, it may provide the only means of reversing the rising trend in runway incursions and near misses on airport surfaces.

### **Biographical Sketches**

Steve Young has been a flight systems researcher at NASA's Langley Research Center since 1987. Since 1993, Mr. Young has been a principal investigator developing avionics systems that enable safe all-weather operations on airport surfaces. This includes directing high-fidelity simulation studies and flight test experiments. Recently, Mr. Young has focused on extending the Synthetic Vision System (SVS) concept employed for this research to all phases of flight to reduce the likelihood of Controlled Flight into Terrain (CFIT). Mr. Young is a member of the Institute of Navigation and is co-chair of a joint RTCA/EUROCAE committee established to define requirements for terrain, obstacle, and airport mapping databases for aviation uses.

Denise Jones has been a research engineer at the NASA Langley Research Center since 1983. For the past eight years, Ms. Jones has served as principal investigator for runway incursion prevention and airport surface capacity research. Ms. Jones has led flight test activities at the Atlantic City International Airport in June, 1995, at Atlanta's Hartsfield International Airport (ATL) in August, 1997, and the Dallas-Fort Worth International Airport (DFW) in October, 2000. Prior to this assignment, Ms. Jones has conducted human factors display research including several piloted simulation studies. Ms. Jones is a member of the American Institute of Aeronautics and Astronautics and is currently serving on the Aircraft Operations Technical Committee.

## Acronyms

|         |  |        |  |
|---------|--|--------|--|
| ADS-B   | Automatic Dependent Surveillance<br>– Broadcast        | GPS    | Global Positioning System                          |
| AGL     | Above Ground Level                                     | HUD    | Head-up Display                                    |
| AMASS   | Airport Movement Area Safety<br>System                 | LAAS   | Local Area Augmentation System                     |
| AMDB    | Airport Mapping Database                               | NASA   | National Aeronautics and Space<br>Administration   |
| ASDE    | Airport Surface Detection<br>Equipment                 | ND     | Navigation Display                                 |
| A-SMGCS | Advanced Surface Movement<br>Guidance & Control System | NTSB   | National Transportation Safety<br>Board            |
| ATC     | Air Traffic Control                                    | RIAAS  | Runway Incursion Alerting and<br>Advisory System   |
| ATIDS   | Aircraft Tracking & Identification<br>System           | RSM    | Runway Safety Monitor                              |
| ATL     | Hartsfield-Atlanta International<br>Airport            | RCA    | Runway Conflict Alert                              |
| CEP     | Circular Error Probability                             | RTA    | Runway Traffic Alert                               |
| CFIT    | Controlled Flight Into Terrain                         | RTCA   | Requirements & Technical<br>Concepts for Aviation  |
| CPDLC   | Controller Pilot Data Link<br>Communications           | RWSL   | Runway Status Lights                               |
| DFW     | Dallas-Fort Worth International<br>Airport             | SA     | Situational Awareness                              |
| EMM     | Electronic Moving Map                                  | SMA    | Surface Movement Advisor                           |
| EUROCAE | European Organisation for Civil<br>Aviation Equipment  | STIS-B | Surface Traffic Information Service<br>– Broadcast |
| FAA     | Federal Aviation Administration                        | SVS    | Synthetic Vision System                            |
| FMS     | Flight Management System                               | TCAS   | Traffic Alerting & Collision<br>Avoidance System   |
| FTE     | Flight Technical Error                                 | UAT    | Universal Access Transceiver                       |
| GBA     | Ground-based Alerting                                  | WAAS   | Wide Area Augmentation System                      |



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